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SIMULATION OF BULK MINING AT DEPTH WITH BACKFILL IN ONTARIO MINES

Final Report - Volume 1

EXECUTIVE SUMMARY

by

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ABSTRACT

This report details the mathematical formulations developed for the implementation of localized plastic behaviour and multiple material behaviour into the boundary element technique. The report presents the findings of investigations on the suitability of various representations for these components in a three-dimensional formulation. The development was first conducted for a two-dimensional formulation which was embodied in the numerical program MINE2D. The findings from testing of this development were then used as a basis for the three-dimensional formulation and development of program MINE3D. Testing was then performed on the three-dimensional components. Example analyses are presented which demonstrate the accuracy of each of the various formulations in MINE2D and MINE3D.

Continuous, piecewise linear strength elements were required rather than discontinuous, constant strength elements because constant elements were found to behave poorly for large plastic deformations, whereas linear elements demonstrated reasonable accuracy and behaved well for plastic yield. The use of linear elements necessitated the implementation of a special algorithm to handle the singular surface stress integral at surface nodes. For the three-dimensional formulation, an offset node algorithm was developed which calculates the integral at a small distance from the surface node measured along the average normal at the node.

The elastoplastic character of the medium was modelled using an initial stress formulation. This was found to be a reasonable scheme provided that only very localized regions of plastic yield are analyzed. The approach requires extensive discretization or higher-order elements to provide an accurate calculation for displacement fields involving large-scale plastic collapse. This, however, is not feasible for three-dimensional analysis within present computer memory constraints.

Different algorithms were investigated to model multiple materials. In two dimensions, volume elements were used to represent different materials as well as plastic regions. A more efficient approach was developed for the three-dimensional formulation whereby different materials were treated as separate boundary element domains with interactions only through their boundaries.

Finally, the development of the three-dimensional formulation in MINE3D required a significant variation from the two-dimensional formulation in order to reduce storage requirements for the boundary element coefficients. The conventional formulation used in MINE2D would use an enormous amount of computer memory if extended to a three-dimensional formulation for plasticity, making the solution of mine-scale size problems essentially impossible for computer hardware systems typically available to mining organizations. An alternative approach, used for MINE3D, was to restrict the geometric shape of the boundary elements to

parallelepiped shapes. This results in a significant reduction in the memory requirement. Unfortunately, an investigation of typical hardware systems found that even for the parallelepiped scheme, present systems have a substantial degradation of performance rate when accessing the required memory for coefficient storage. The consequence of this finding is that the size of problem which can be solved with the three-dimensional formulation in MINE3D is still quite restrictive (smaller than approximately 2000 boundary element nodes). MINE3D can only be used on a practical basis when larger core memory or faster disk hardware becomes available.

RÉSUMÉ

Ce rapport présente les formulations mathématiques développées pour le couplage de la technique des éléments frontières avec le comportement plastique de matériau et la modélisation de matériaux multiples. Ce rapport présente aussi les résultats de recherches sur les représentations appropriées de ces techniques dans le cadre d'une formulation en trois dimensions. Le développement fut tout d'abord réalisé pour une formulation en deux dimensions, à savoir de programme MINE2D. Les résultats des tests de ce programme ont servit de bases pour la formulation en trois dimensions, et ont conduit au développement du programme MINE3D, puis aux tests de celui-ci. Des exemples d'analyses sont présentés, lesquels démontrent la pertinence de chacune des deux formulations de MINE2D et MINE3D.

Des éléments à la résistance linéaire continue par intervalle ont été utilisés plutôt que des éléments à la résistance discontinue et constante par intervalle, ceux-ci n'étant pas satisfaisants pour représenter les larges déformations plastiques, au contraire des premiers plus précis. L'utilisation de ces éléments a nécessité le développement d'un algorithme particulier permettant de tenir compte de la singularité des contraintes aux noeuds de surface. Pour le cas de la formulation en trois dimensions, un algorithme de reject de noeud a été développé pour calculer l'intégrale à une courte distance de noeud de surface mesuree le long de la normale moyenne au noeud.

L'élastoplasticité du milieu a été modélisée par une formulation du type de contraintes initiales. Cette approche est justifée dès que l'analyse plastique porte sur des régions trés localisées. Elle requiert néanmoins une discrétisation trés élévée ou des éléments d'un ordre supérieur pour permettre un calcul précis dans le cas de champs de déplacements impliquant une plasticité de grande échelle. Ceci n'est cependant pas possible dans une analyse en trois dimensions sans problème de mémoire d'ordinateur.

Plusieurs algorithmes ont été envisagés pour modéliser les matériaux multiples. En deux dimensions, des éléments de volume ont été utilisés pour représenter tant les différents matériaux que les régions plastiques. Une méthode plus efficace a été développée pour la formulation tridimensionnelle, dans laquelle les différents matériaux ont été représentés comme autant de domaines d'éléments frontières distincts, interagissant seulement au travers de leur frontières.

Finalement, de développement de la formulation tridimensionnelle de MINE3D a nécessité des changements significatifs de la formulation bidimensionnelle, afin de minimiser la mémoire allouée aux coefficients des éléments frontières. La formulation conventionnelle de MINE2D, étendue à MINE3D, serait prohibitive en terme de mèmoire d'ordinateur, rendant impossible la modélisation de problèmes à l'échelle d'une mine pour le type d'ordinateurs

usuel aux mines. Une alternative fut de restreindre la forme géométrique des éléments frontières à celle de parallépipèdes. Le résultat fut une réduction trés signifcative de la mémoire requise. Néammoins, un examen des systèmes d'ordinateurs montra que même cette alternative réduisait encore largement les performances par la mémoire importante toujours requise.

La conséquence de ce résultat est que la taille d'un problème qui peut être étudié par la formulation tridimensionnelle de MINE3D est encore trés restrictive (inférieure à environ 2000 noeuds d'éléments frontières). MINE3D pourra seulement être utilisé sur une base pratique guand des mémoires plus étendues ou disques plus rapides seront disponibles.

PREFACE

This project entitled "Simulation of Bulk Mining at Depth in Ontario Mines with Backfill" consists of two major components: the development of a numerical model, and field verification of the model. The project, which began in 1986, was expected to take four years ending in September 1990 but was extended until March 1991. This report is the second of six volumes which describes the results of the project.

The work was initiated by INCO Limited and is partially funded through the MDA Program (joint Canada-Ontario Mineral Development Agreement, DSS file 14SQ.23440-6-9033). The project is administered by Canmet and their assistance is greatly appreciated.

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EXECUTIVE SUMMARY

1.0 INTRODUCTION

The project "Simulation of Bulk Mining at Depth with Backfill in Ontario Mines" was an extraordinarily ambitious one. The project began in October 1986 with the principal objective of developing a fully three-dimensional numerical model using the Boundary Element Method with plasticity. It was intended to fill a gap in existing numerical codes to which were unable to effectively simulate mining geometries in three dimensions. To date, there is still no such code commercially available using this numerical technique.

The intention was not only to develop a functioning code but to calibrate that code against an intensely monitored bulk mining area in Creighton Mine. The field monitoring programme at Creighton was also very ambitious. To date, there is no bulk mining operation in Canada, perhaps in the world, which has been monitored by such an extensive array of sensors and with such a wide variety of instruments and techniques over such a prolonged period.

A functioning numerical code was developed and the results of the field monitoring programme were compared to numerical modelling results. However, the computing requirements of the numerical model are such that it is applicable only to very small problems and the plethora of instrumentation data is difficult to interpret and indicates that the displacement of blocks within the rockmass plays a significant role in the rockmass response to mining. As a result of the computer limitations of the model and the continuum limitations of the code, calibration of the field results and the model results was severely limited.

As the project progressed it was recognized that some aspects of the original scope could not be fully accomplished and had to be abridged. Some requirements were eliminated and others were replaced by alternative methods and techniques so that the abridged scope reflected what could realistically be achieved. Throughout the project the field monitoring programme was adversely affected by the severity of the rock conditions at depth and by the very difficult operating environment and the model development was severely disrupted by personnel problems just over half-way into the project.

The total cost of the project was originally budgeted to be $2,005,859, with a fixed cost to Canmet of $1,000,000 and the remaining cost to Inco of $1,005,859. The final cost of achieving this reduced scope was approximately $2,622,600, a cost over-run of

over 30% of the original estimate. While the costs charged to Canmet consisted of operating labour and consumables, Inco's cost included capital expenditures on computer equipment of $399,600 and $1,223,000 on operating labour, consumables and consultants.

The principal source of the cost over-runs was the field monitoring portion of the project, where the ground conditions and operating conditions proved to be much more difficult than anticipated. However, the responsibility for the success or failure of any research project ultimately lies with the project management, in the broadest sense. Many of the problems which developed could have been foreseen if standard project management techniques had been employed. It was the failure of the project managers to appropriately monitor the progress of the project so as to correctly identify the technical and personnel problems which were developing, which led directly to the cost over-runs and the revision of the project scope. The failure to correctly identify the nature of problems made it impossible to introduce the necessary strategies in a timely and effective way in order to overcome these difficulties and to adjust the project priorities and objectives appropriately.

Technically, the project was divided into three distinct parts; the development of the numerical model, the field monitoring programme and the calibration of the model results against the results of the field monitoring. These aspects of the project are discussed in great detail in Volumes 2, 3 and 4, respectively, of the Final Report. This part of the Report, in addition to a brief summary of these parts of the report will consider the overall management of the project.

2.0 MODEL DEVELOPMENT

By the mid 1980's, Inco had recognised the limitations of purely elastic models for gaining an understanding of the behaviour of a highly stressed rockmass like that at Creighton Mine. At that time there was no commercially available numerical code which could routinely be applied to this kind of mining problem. The requirements of the model were to take account of the truly three-dimensional shapes of the mining excavations, to analyze their interaction and to simulate the effect of the non-elastic behaviour of several materials such as rock, ore and backfill.

At that time, it was thought that the Boundary Element Method, which had been successfully employed to provide Inco with a fully three-dimensional elastic model (Bem3D), offered the best hope of satisfying these requirements in a model which could be run routinely to solve typical mining scale problems. The result of this research effort is the Mine3D model which has two distinguishing features; the ability to simulate localised regions of failure within an elastic continuum, and the capability to model interacting regions of different material types which permits the simulation of backfill placement.

The model was developed in three distinct stages; the development of the fundamental formulation of the boundary element method, the development of a two dimensional version of the code (Mine2D) and the three-dimensional version (Mine3D). Most of the mathematical formulations and the 2D code were completed by Dr. T. Wiles in the first three years of the project. In the final year of the project the three-dimensional code and some associated formulations were developed by associates of the Itasca Consulting Group Inc. of Minneapolis.

2.1 Developments in the First Three Years

The early stages of this part of the project proceeded with no significant alterations or revisions to the original plan. Some 16 months after the start of the project, it had been shown that the boundary element technique could effectively be used to simulate the localized elastic-plastic behaviour of infinite media. Furthermore, the accuracy of the results indicated there was good potential for success with this approach although it was also clear that further development work was required for yielding pillars.

In October 1988, two years into the project, the 2D version of the code had successfully analyzed verification cases and was ready to be applied to mining problems. However, it had also become clear that discontinuities played a major, if not dominant role, in the failure of the faulted and intensely jointed rockmass at Creighton Mine. It was therefore decided to extend the technique to accommodate displacement discontinuities in order to simulate the

behaviour of major fault structures or a limited number of pre-existing joints.

By September 1989 most of the research in numerical methods was thought to be complete and only the development of the final versions of the Mine2D and Mine3D models remained. However, the development of the constitutive relationships to describe the behaviour of different failed materials such as rock, ore and backfill had only just begun.

Because of management problems within the project which will be discussed in detail in Section 5, further development of the Mine2D code was abandoned in order to try to ensure the completion of the Mine3D code by the original delivery date.

2.2 Developments in the Final Year

In November 1989, the Itasca Consulting Group took over the task of the final development of the Mine3D code. Itasca committed to completing a basic functioning code, verification analyses and reports by the original submission date. However, based on their limited experience with this particular code at the time the sub-contract was let, they were not prepared to commit to including three features in the code, namely the fault-slip option, the multiple regions option and the large strain option. The task to include these features in the code was listed in the project schedule but the work was not scheduled to be done before September 1990.

At the outset, Itasca decided to adopt the approach of developing three separate programs for input, analysis and output called MIP (Mine3D Input Program), MAP (Mine3D Analysis Program) and MOP (Mine3D Output Program). The conversion of the two-dimensional code to a three-dimensional version proceeded according to schedule until March 1990, when it was discovered that the double-node solution used in the 2D code was not suitable for the 3D version and in April this was changed to an 'average node' calculation.

In May 1990, at a meeting with Canmet in Ottawa, it was agreed to make three modifications to the scope of work required in the Itasca sub-contract. The modifications were that the multiple regions option not scheduled in the original sub-contract, would be completed by the original submission date of September 1990, that the large strain option would not be required since tests had indicated this would not be useful and, finally, that element geometry be limited to equal-sized parallelepipeds in order to greatly reduce the computer requirements of the code.

In June, Canmet and the DSS granted an extension to the final submission date from September 30, 1990 to March 31, 1991, in order to include the optional tasks outlined in the sub-contract schedule

and to allow time for calibration of the code with the results of the field monitoring programme.

In September 1990, the first version of Mine3D was completed and delivered along with the results of verification analyses. It was then agreed by all concerned that Itasca would proceed with the additional tasks of the fault-slip option, optimization of the coefficient matrix and final code preparation and training materials. These tasks were then formally scheduled in the project report forms provided by Itasca.

Most of the development work had been done on 80386 PC's, with the intention of converting the code for use on the Vax computers at Inco and Canmet. However, the increasing frequency and severity of equipment failures of the Inco's Vax computers indicated that relying on this equipment at this critical stage in the project might not be prudent. In order to ensure the reliability of computer equipment which was compatible with both Itasca and Canmet equipment, Inco purchased a Sun SPARCstation 2 computer.

2.3 Developments during the Contract Extension

Unfortunately, in November 1990, two serious errors in the analysis program MOP were identified. Firstly, the 'average node' calculation which had been introduced by Itasca in April in order to solve the double-node calculation problem, was found to be geometry-dependent. A new solution to the problem, using a fictitious force calculation at small distance along the normal to the node was successfully introduced. The second problem was that the conditions to ensure convergence using the original matrix solution method, the Gauss-Seidel method, could not always be met. The problem was eventually resolved but only after alternatives such as LU decomposition had been investigated and valuable time had been lost. And, finally, compatibility problems with Canmet computers had to be resolved by Itasca purchasing a Lahey compiler in addition to the SVS Fortran compiler which had been used throughout the code development and then to convert some of the routines.

By January 1991, it had become clear that the run-time and memory requirements of the code were much greater than had been expected. The principal problem was the time required to access the virtual memory to store and retrieve the coefficients from the boundary element matrix. The effort expended in trying to resolve these difficulties made it impossible to test the multiple material logic or to work on the fault-slip option. These problems made it impossible for Itasca to work on the development of the fault-slip option in the 3D version of the code as had been intended. In February, it was agreed with Canmet that the fault-slip option could not be accomplished within the time available and that the requirement for this option in the Scope of Work be dropped.

In March 1991, the principal deliverables, the current version of the Mine3D code (MIP, MAP and MOP) and a draft User's Manual, were submitted. Thereafter, no further development work on the code was performed although minor adjustments and corrections continued to be made until June 1991 when the Lehay-compiled source code for the final version was submitted.

Itasca and Inco continued to work on the Mine2D version of the code, the Users Manual's for both the Mine2D and Mine3D codes and the final report on code Development until August 1991. In October 1991, the Showpartner training module was delivered to Inco and then submitted to Canmet.

2.4 Conclusion

The Mine3D program has two major distinguishing features: the capability to simulate localized zones of plastic yield which are defined within an elastic infinite body; and the ability to define multiple regions of different material types, thus permitting the simulation of backfill placement. Mine3D is formulated such that sequential calculations can be made in order to simulate progressive mining steps involving excavation and backfill. The complete stress state, total displacements and energy release at each step are calculated so that an evaluation can be made of the effect of each mining step. The plasticity influence on stress history is remembered in order to include load path dependency in the solution.

Unfortunately, the computational price that must be paid to utilize these features in the boundary element method is enormous. The size of the influence coefficient arrays that must be created in order to perform a plasticity analysis if conventional quadrilateral-shaped elements are used is substantially greater than that for an elasticity analysis. In order to reduce array sizes to a manageable level, a parallelepiped geometry was imposed in the boundary element formulation. By restricting the element geometry, the number of elements which can be modelled within the same storage requirement as that for arbitrary elements is increased dramatically. The nature of bulk mining is such that regularly-shaped excavations are the norm, and the vast majority of problems can be simulated with elements which are restricted to equal-sized parallelepipeds.

Using parallelepipeds changes the coefficient storage relation from a quadratic function of the number of boundary element nodes to a linear function. Although this results in greatly reduced storage requirements, the coefficient array size is still large. For three-dimensional problems in bulk mining, the number of elastic surface elements and plastic volume elements can easily be between 10,000 and 100,000 elements. Even with the parallelepiped approach, coefficient arrays can be of the order of 200 Mbytes and higher.

The reason for the great number of boundary elements is the requirement in plasticity analysis to have a fine nodal discretization in the region of anticipated plasticity since the grid of volume elements must be sufficiently fine to calculate the stress gradient and plastic deformation accurately. Although the parallelepiped geometry provides a substantial reduction in the coefficient arrays, the number of parallelepiped elements needed for plasticity problems is still large, because the element geometry is uniform throughout the entire modelled region. The approach does not directly permit varying the parallelepiped grid spacing. Consequently, the element spacing required for modelling the localized plasticity accurately must be used throughout the entire model.

In addition to coefficient array size restrictions, plasticity in the boundary element method also imposes a considerable increase in the number of calculations required for problem solution as compared to the number required for elastic-only boundary elements. The number of calculations for each solution iteration step is increased by at least a factor of 32 for all the required stress components for the plastic solution. Additionally, displacement calculations and plasticity adjustment calculations are also required.

The storage requirement and calculation intensity necessitates the operation of Mine3D on a computer system with facility for large memory for array storage and rapid access of array coefficients. Unfortunately, current computer hardware systems typically available to mining organizations are not capable of providing sufficient memory for array storage without a substantial degradation in performance rate for disk access. A considerable effort was made to try to enhance the array access speed by optimizing the ordering of the arrays in software. However, this effort did not provide a sufficient increase in speed to make feasible the practical solution of problems containing more than approximately 2,000 surface nodes.

Collectively, these factors pose a fundamental dilemma to the application of a three-dimensional boundary element code with plasticity. While in principle Mine3D can simulate problems associated with bulk mining in massive orebodies, the practical application of this program to actual mining conditions is severely restricted and the application of Mine3D to a field-scale analysis of mining problems remains prohibitive.

3.0 FIELD MONITORING

It was because of the inability of existing models to efficiently analyze the stability problems at the deepest levels of Creighton Mine that this model development project was devised. It seemed obvious that the field calibration of the model should be based on data obtained from this mine. When the project proposal was being developed, a major change in the mining method at Creighton was being introduced and a novel concept of excavating a destress slot had been implemented in order to facilitate ore extraction under the high stress conditions at depth. Although the destress slot had been extracted and filled by the time the instrumentation could be installed, it was believed that the process of mining progressively away from the destress slot would still provide unique and invaluable information about the mode of failure of a highly stressed rockmass.

3.1 Location of Monitoring Site

The principal monitoring site was located at Creighton Mine between 2200m and 2244m below surface (from the 6600 ft. level to the 6700 ft. level) in an area known as the 4500 VRM block. This block was some 83m square on plan and about 53m high and was located to the east of the 7m wide destress slot which had been mined from hangingwall to footwall of the orebody. When the instrumentation was installed in 4500 block, most of the essential access development had been completed and the instruments could be installed in locations which were remote from mobile equipment travel routes and were protected from air blast concussion.

The same was not true of the secondary site, the 4000 VRM block which was located from 2300m to 2400m below surface (7000 ft. level to 7200 ft. level). This area was still in the development phase and instrumentation could not be installed in locations which could be protected from damage from mobile equipment or blast concussion. After several attempts to install and protect instrumentation had failed, the effort to use this area as a monitoring site was finally abandoned.

3.2 Monitoring Techniques

The monitoring of the 4500 block site falls into two broad categories; instrumentation and observational techniques. The instrumentation consisted of rock displacement measurements, rock stress measurements, rock stress monitoring and backfill pressure monitoring. The observational techniques used were bore-hole logging using a TV camera and video, scan lines and subjective records of the deterioration of the surface of the excavations and the production boreholes within the monitoring site. Together, these categories were combined to draw conclusions about the nature

and extent of the stress-relaxed zone around the mined-out area and the migration of this zone with time.

Of the instrumentation methods which were used, the backfill pressure measurements proved to be the least successful. This was largely because of the difficulty in protecting the cables connected to the earth pressure cells, but even when those connections were maintained, the cells failed to provide meaningful information.

The attempts to determine the nature and extent of the changes to the stress regime induced by mining at depth was also largely unsuccessful. The original intention had been to make fifty over-coring measurements throughout the course of the project and although thirty-seven cells were actually recovered, only three successful measurements were made. The principal difficulty was that the rock was simply too highly stressed to provide a suitable site to install and recover the hollow inclusion cells. However, in order to try to obtain some information about the stress changes induced by mining, the hollow inclusion cells were installed and continuously logged to monitor the stress changes which were taking place. This technique proved to be very successful, providing thirteen successful sets of results for twenty-one installed cells.

The displacement measurements included extensometers as well as inclinometers. The inclinometers were more difficult to install, required more effort to collect information and were less likely to provide reliable data. Even the data which appeared to be reliable was often difficult to interpret or was not consistent with other results. The multi-point extensometers were relatively successful, providing a large, continuous record of the timing and location of extremely small movements.

3.3 Qualitative Observations

In terms of assessing the extent of the stress-relaxed zone around the mined-out areas, the bore-hole logging and subjective assessments of the production bore-holes proved to be by far the most valuable. The difficulty in this case was not the collection or interpretation of the results but rather finding a means of displaying the data in a way which would be meaningful to someone not already intimately familiar with the monitoring site.

This information was in two forms; the borehole break-out caused by high stresses and the general break-up and deterioration of the hole caused by the opening up of joints and fractures, indicating the existence of low-stress conditions. By observing and recording these conditions in the boreholes it was possible to identify the extent of the low-stress zones around the mined-out areas and to locate the zone of highly stressed ground which generally forms an envelope around the stress-relaxed zone. In addition to locating

the existence of high stresses, bore-hole break-out also provided information about the direction of maximum principal stress in the plane perpendicular to the bore-hole axis and it was therefore possible to track the changing orientation of the maximum principal stress due to the extraction of the production stopes.

3.4 Conclusion

Despite the lack of success with some of the monitoring techniques, the field monitoring program has nevertheless provided a wealth of information about the behaviour of a highly stressed rockmass in response to bulk mining at depth. Assuming the technical problems of computer run-time and storage will be overcome in the near future, analysis of this data over the next few years may well play an important role in the development of a numerical model which can be routinely applied to typical mine-scale geotechnical problems associated with bulk mining at depth.

4.0 MODEL CALIBRATION

This part of the research was to be the culmination of the entire project and was therefore the most ambitious. The original purpose was to simulate the behaviour of the rockmass at Creighton in response to bulk mining and backfilling at depth. This was to have been accomplished using the newly developed Mine3D code and the quantitative results obtained from the field monitoring programme.

In the later stages of the project it became clear that there would be insufficient time to conduct a great deal of quantitative comparison of field data with model results and it was agreed that qualitative comparisons would be sufficient. Unfortunately, as a result of the unexpected difficulties with the final code development, no useful comparisons using this code could be made. The development of a working version of the Mine3D code was delayed and continued right up to the end of the project. Even then, the final working version of the code required such large computer requirements that only a very simple model of the destress slot could be run. The installation of instrumentation boreholes used to monitor the field site took place after the destress slot had been mined and filled and there very little objective data about the rock response to this stage of mining.

However, since it clear that the model does actually function if sufficient computer resources can be made available, how should the resources which ought to be made available in order to apply Mine3D be determined? The other numerical codes which are available, and which require fewer resources, can provide only partial answers to the kind of complex 3-dimensional geotechnical mining situation exhibited in the Creighton field monitoring site. The measure of the usefulness or applicability of Mine3D becomes a trade-off between the validity of the partial solutions and the cost of the additional resources to achieve the complete (Mine3D) solution. If these codes can provide most of the answers and the additional cost to obtain the complete solution from Mine3D is very large, then the use of Mine3d will be unattractive. If, on the other hand, the cost of additional resources is small and the other codes can offer little or no insight into the problem, then Mine3D will be attractive.

4.1 Methodology

The limitations of existing codes became apparent almost immediately and it was not possible even to make simple comparisons of the these codes to the field results. The different numerical codes had to be compared to the field data in completely different ways. For example, the elastic Bem3D model does not calculate displacements and therefore only the stress magnitudes and factor-of-safety contours could be compared to the location of the stress relaxation zones determined in the field and no comparison to the displacements calculated by other codes was possible. Since the

actual field site was not a suitable plane-strain case, it was not reasonable to expect the stresses and displacements calculated by the 2D codes to accurately reflect the field values.

In the field, the stress relaxation zones are areas where either the rockmass had actually failed in response to mining or where the mining geometry had created stress shadows in areas that had not failed. In both cases these areas were no longer in a state of high stress. Since such a highly stressed rockmass is being actively mined, the tendency is often to assume that failure has occurred but on the basis of the evidence available in the field it was generally not possible to distinguish between the two possible causes of the low stress in a particular area. Consequently, the designation 'stress relaxation zones' generally means zones of low stress and is not meant to imply that the area has failed.

The limitation of some of the codes resulted in them only being generally comparable to each other based on their estimated location of the stress relaxation zones which were measured at several different stages of mining during the monitoring program. The plastic codes all plotted failure and stress contours which were compared directly to the monitoring data. The BEM3D elastic model does not calculate failure and, therefore, could be compared only to the monitoring data by assuming that a factor of safety of one in the factor of safety contour plots was equivalent to the failure zones.

In attempting to calibrate the numerical codes the approach was to first define the input parameters (rock mass strength, friction angle, elastic modulus, cohesion, etc.) for the given code by modelling a known rockmass response from the monitoring site. These input parameters were then used in the modelling of the different stages of mining in the monitoring site and compared to the displacements, stress magnitudes or failure zone locations obtained from the field measured data. The codes were then compared on the basis of their ability to match the data measured or determined in the field and the degree to which the input parameters used in each code agreed with values obtained from the field and from laboratory testing.

4.2 Calibration of Field Results

Since it was not feasible to use the Mine3D code to analyze the field site excavation sequence, the only issue which could be addressed by this part of the project was the value of the partial solutions offered by the other available codes such as Bem3D, Flac, Mine2D and 3Dec.

4.2.1 BEM3D

The Bem3D code is a three-dimensional, elastic boundary element code. It continually underestimated the extent of failure that will result from the response of a given rockmass to progressive bulk mining. Even with weaker rockmass properties the model could not simulate the behaviour measured in the rock mass by the monitoring program. The redistribution of stress in the monitoring area which occurred in response to rockmass failure and block movements caused by mining proved to be beyond the capability of an elastic continuum code to simulate and the obvious consequence was a poor agreement between the model and the field measured data.

4.2.2 FLAC

Flac (Fast Lagrangian Analysis of Continuum) is a two-dimensional, explicit differential code with plasticity. There were three 2D modelling geometries of the case study site calibrated against the field data and the input parameters for the rock mass properties for the three models were identical. However, none of the sections selected for Flac modelling exhibited the plane-strain conditions necessary for reliable two-dimensional modelling. Also, the models could not take into account the effect on the stresses and displacements in the crown pillar of the previous mining in areas adjacent to the monitoring site.

Consequently, there were some significant discrepancies between the model results and the instrumentation data. The displacements predicted by the Flac models were about 30% less than those actually measured by the extensometers and inclinometers and the predicted stress magnitudes about 20% less than the underground stress measurement data.

The vertical sections (longitudinal and cross-section) were used to simulate the behaviour of the crown pillar between 6600 and 6700. The models indicated failure of the pillar at about 30m thick which agrees well with the observations in the field. However, in order to accomplish this correlation it was necessary to reduce the vertical stress transfer through the surrounding backfill material by 50%, by effectively decreasing the stiffness of the backfill to unrealistic levels. Even then the nature of the failure did not agree with the observations. Both sets of results indicated a gradual failure of the crown pillar originating at the lower part of the footwall contact progressing diagonally towards the upper part of the hangingwall contact. The actual failure of the pillar was observed to have been relatively sudden, culminating with the occurrence of a large rockburst in October 1987.

The plan section model could not be used to simulate the failure of the crown pillar but was used to determine the shape of the failure zone around the mined out stopes. Although the effects of the

upper and lower mining areas could not be taken into account, the shape of the failure zone predicted by Flac generally agreed with the information obtained from the monitoring site by the borehole camera stress monitoring cells.

4.2.3 Mine2D

The mine2D model is a two-dimensional boundary element code with plasticity. Again, the geometry of the field site was not well suited to two-dimensional monitoring and in addition the relatively smaller vertical height of this particular model may have had an even greater effect on the results. A sensitivity analysis of the input parameters showed that a reduction in the strength of the ore had very little effect on the results which were very sensitive to changes in the strength assigned to the backfill/rib-pillar composite material which was arbitrarily selected. It appears unlikely that the input parameters used for the Mine2D models would be suitable for the Mine3D plasticity code. A major part of any future work should include a detailed analysis of appropriate parameters for this composite material which appeared to have a large influence over the size of the failure zone immediately below these areas.

Failure of the crown pillar as simulated by Mine2D occurred when the thickness of the pillar was similar to that observed in the field. In the model the failure occurred as a diagonal shear and the location of the failure zone was consistent with the location of rock damage observed on the field. However, just as with Flac, Mine2D results indicated a progressive failure rather than the sudden failure observed in the field. Generally, the models indicate that the behaviour of the overall geometry is stiff relative to the pillar stiffness while field observations suggest that the overall mining geometry was soft relative to the stiffness of the crown pillar.

4.2.4 3Dec

The excessive run time required for the Mine3D calculation precluded the application of this code to the field site results in the time available after debugging was completed. However, given that the geometry required a three-dimensional simulation, it seemed reasonable to attempt to simulate some of the field site configurations with a 3D model. The 3Dec model is an explicit distinct element code with plasticity and although it can simulate a discontinuous rockmass, it was used only in a continuum mode.

The model was used to simulate a series of excavation geometries from before the mining of the destress slot through the crown pillar, to mining stage 8, when a total of six VRM panels had been excavated and filled. A simulation of the conditions prior to the excavation of the destress slot indicated a major part of the crown

pillar had failed and simulating the mining of the destress slot indicated a relatively small change in the size of this failure zone. The zone of low stress which develops extends only one slot width beyond the boundary of the excavation. With the extraction of the first VRM panel, the stress relaxation zone extends about one half of a panel width around the excavated panel which is very consistent with field observations. As the extraction of the subsequent panels proceeds the model indicates the shape and extent of the stress relaxation zone around the panels is qualitatively consistent with the observations in the field.

4.3 Conclusion

There were major limitations with the ability of all of the models used for calibration to simulate the field site data and this speaks to the need to develop a truly three-dimensional plasticity code. Although the 2D plastic codes were able to generate a failure zone or stress relaxation zone around excavations which was qualitatively similar to that observed in the field, these must be suspect because of the unsuitability of the actual geometry and because of the arbitrary selection of material properties. The 3D elastic code was inherently unable to take account of the redistribution of stresses in response to material failure.

However, all of the codes used in the calibration were continuum codes, or in the case of 3Dec, were used in a mode which assumed a continuum. The field data strongly indicated that the movement of blocks played a significant role in the response of the rockmass to mining at depth.

5.0 PROJECT MANAGEMENT

The work on the model development and the field monitoring programme began in October 1986. Within Inco, the responsibility for overall project management and liaison with Canmet fell to Dr. T. Wiles, the principal investigator on the project. In addition, Dr. Wiles was also responsible for Model Development, while responsibility for the Field Monitoring Program fell to D.A. Landriault.

This management structure continued until half way through the third year of the project, April 1989, at which time D. Morrison formally took over responsibility for project management while Dr. Wiles and D. Landriault continued to be responsible for code development and field monitoring, respectively. In October 1989, after Dr. Wiles had announced his intention to resign from Inco in January 1990, responsibility for code development shifted to the Itasca Consulting Group Inc. of Minneapolis. The responsibilities of D. Morrison, D. Landriault and the Itasca Consulting Group then continued to the end of the project.

5.1 Overall Project Progress

In order to monitor the progress of the project, the Department of Supply and Services provided a contract and plan form (DSS-MAS 9143). These forms were to be submitted along with the claims forms for reimbursing Inco for the operating costs as part of the Contract. The original proposal and contract included the requirement for monthly progress reports. However, almost immediately following the letting of the contract, it was agreed with Canmet to alter the reporting period from monthly to quarterly and this reporting schedule continued to the end of the project. However, it was not the frequency of the project reporting which allowed the project to deviate so significantly from the plan but rather the nature and content of the reports themselves.

The first two years of the project were conducted using the manpower resources of the Rock Mechanics section of the Mines Research Department which existed before the project began. However, the third year of the project called for a major expansion in the number of people working on numerical code and computer graphics developments. For a variety of reasons, this additional manpower in the Rock Mechanics section was not included in the Mines Research departmental budget for the coming year. As a result of the lack of manpower, the progress on code development and computer graphics began to slip.

By April 1989, it had become clear that the project was in serious difficulty. A thorough review of the project was conducted and revealed that the original scope of the project could not be accomplished either before the original submission date or within

the original budget. As a result of this project review, as well as discussions with the Scientific Authority and other Canmet personnel in August and September of 1989, it was concluded that there were two ways in which the project could proceed. One option was that the effort to develop the 3-dimensional code (Mine3D) be abandoned and the remainder of the project resources be devoted to fully developing the 2-dimensional code (Mine2D) which had just been completed. The second option was to abandon any further development of the (Mine2D) 2-dimensional code and devote the remaining project resources to the development of the 3-dimensional code.

It was the recommendation of the Inco personnel, and particularly Dr. Wiles, that the first option, to fully develop Mine2D, be pursued. However, Canmet contended that the only acceptable option from their perspective was to continue with the development of the 3-dimensional code Mine3D at the expense of further development of Mine2D and Inco agreed to comply with Canmet's requirements.

Shortly afterward, Dr. Wiles decided to resign from Inco. After discussions between Inco and Canmet on how to proceed, Inco's proposal to sub-contract the remaining code development to the Itasca Consulting Group of Minneapolis was approved by Canmet. In retrospect, it may have been more appropriate to terminate the project at this time, but based on the assessments of the remaining technical uncertainties, it was agreed that the project should continue. Beginning in November 1989, Dr. Wiles was replaced as the principal investigator and code developer by the Itasca Consulting Group, pending his departure in January 1990.

The objective of the sub-contract was to complete the code development by the original contract submission date, September 1990. However, since none of the calibration work could be done until the code was developed, an extension to the original contract was necessary, and was granted by the DSS and Canmet. However, the contract could only be extended to the end of the Mineral Development Agreement which was in effect only until March 1991. As it turned out, a few important aspects of the code development could not be accomplished in the time remaining. However, this can in no way reflect badly on Itasca. This Group became involved at the most crucial stage of the project, and their technical developments and project management were exemplary. Given that the Itasca Group were able to conduct such a high risk project while maintaining a high degree of control of their part of the project, it is important to examine how control of the original contract came to be lost.

5.2 Project Reporting

In the early stages of the project, when the monitoring and control of the project are the most critical, the project management

techniques applied to this project were cursory and the importance of good project management was either not recognized or at least not acted upon. While the reports did record the progress which had been made and the expenses incurred during that reporting period, little attempt was made to use this information to assess the implications for the overall progress of the project. It was this failure, rather than any subsequent action or decision, which contributed more than any other to the failure to accomplish the original scope of the project.

It is important to understand how this failure could have occurred while, superficially at least, all the mechanisms put in place to monitor the project were being satisfied. One difficulty lies with the shared responsibility between the DSS and Canmet who are primarily responsible for the financial and technical aspects of the project, respectively. This may not be the best mechanism to monitor project progress since the deficiencies in the nature of the quarterly reports could only be identified by integrating the two types of information and examining them in detail. When this was done, it became clear that the field monitoring part of the project had over-expended funds at the expense of the code development and that both the code development and field monitoring parts of the project were behind schedule. The result was that the original project scope could not be accomplished within the original budget because of field monitoring cost over-expenditures and could not be completed before the submission date because of slippage on the code development tasks.

In the case of the model development, the information reported was that part of the technical model development which had been accomplished during the reporting period. However, the estimates of what would be required to complete the project remained unchanged throughout the first two years of the project. Indeed, Canmet received no information to suggest that the code development part of the project was off schedule until June 1989. The expenditures were almost always under-budget and yet it was assumed this was having no significant effect on the progress of the code development work. Identifying the problem earlier in the project would have presented Inco management with the need for increased manpower with sufficient lead-time to modify departmental manpower.

In the case of the field monitoring programme, the amount of time and effort that had been expended on instrumentation and investigation was reported but there was no mention of what proportion of the scheduled work had been successfully completed. For example, it became clear very early in the project that the over-coring programme was not proceeding as planned. The plan called for a total of fifty stress measurements to be made during the course of the project and the prevailing attitude was that since this was a research project the programme should continue until the originally planned result was accomplished.

An analysis of this part of the programme showed that after a great deal of time and effort and over 120% of the task budget had been expended, a technical success rate of only 8% had been achieved, principally because of the adverse conditions encountered in the field. Once this analysis was complete, it was obvious that some change in the programme was necessary; the projected cost of fifty successful results would be prohibitively expensive. Consequently, the over-coring programme was discontinued and replaced by the stress monitoring programme. As a cost analysis would later show, the success rate for this monitoring programme would turn out to be only 62% - a measure of how difficult it is to apply such a sophisticated monitoring technique in a very difficult mining environment. However, since it cost only just over half of the original task budget, this programme was not only more successful but also more cost-effective than the original programme.

Thus, the quarterly reports indicated that money was being spent in the field but did not indicate that in some cases very few results were being achieved. The 'revised' estimate to completion quoted in each quarterly report was not a revised estimate, but was merely the original cost estimate minus the costs to date. It did not reflect any revision to the planned estimate based on the experience gained as a result of the actual work performed up to that time. The consequence of this kind of cost reporting was that the reports continued to indicate that the project was exactly on schedule when this was not, in fact, the case. For example, if a particular task is budgeted at $250,000 and none of the expected results have been achieved after $100,000 has been spent, then the revised 'estimate to completion' should be $350,000. This would reflect the expenditures and the failure to accomplish any part of the task while reporting a revised estimate to completion of $150,000 suggests that the technical results are going according to plan. It was the project managers' fundamental misunderstanding of the purpose of the Project Report Form which allowed control of the project to be lost.

Another source of information indicating the actual progress being made on the project was contained in the quarterly claim forms. In addition to the total labour charges, the quarterly reports clearly indicated the distribution of labour charges among the four types of labour; specialist, engineer, technician and miner. These quarterly labour charges could have been compared to the projected figures in order to identify any deviation from the expected expenditures. Had such a comparison been made early in the project, it would have revealed the over-expenditures on the field monitoring programme and the under-expenditures on the model development part of the project. However, since the agreement with Inco was that once the ceiling price was reached, all further costs would be borne by Inco, the interest of Canmet and the DSS lay primarily in the total expenditures. So long as the total expenditures to date did not exceed the ceiling price, it was assumed the project was proceeding as planned.

5.3 Conclusion

It is a common misconception among scientists and engineers that project management is nothing more than menial administrative work which falls far below the level of priority of the technical work. Competent, professional project management as a means of monitoring and controlling technical work is an essential component of any major project. The more technically demanding the project and the greater the risk of the project not proceeding according to plan, the greater the need for good project management. It is also essential to provide for the monitoring and control of the work from the very beginning of the project, the time when there is the greatest flexibility and a variety of options can be exercised. Introducing management analysis and control half way through a project cannot compensate for its absence early in the project.

Some of the necessary mechanisms were instituted by the Department of Supply and Services by way of their Contract Plan and Report Form. However, in performing their monitoring function, the DSS could do little more than accept at face value the information presented to them. That this information did not properly reflect the nature of the technical progress being made on the project is primarily the responsibility of Inco Management and Canmet. Only those with a complete understanding of both the technical and financial aspects of the project can be expected to identify problems as they developed and to take action to bring the project to a successful conclusion.

That the principal objective of so ambitious a research project was not accomplished should not be regarded as failure. By its very nature research is an endeavour in which technical success is not assured. However, it is incumbent upon all those involved in a research project to try to ensure that the lack of success is due to the technical uncertainties inherent in the research and not to the management of the project.

6.0 RECOMMENDATIONS

The degree of success of the project "Simulation of Bulk Mining at Depth with Backfill in Ontario Mines" provides two important lessons for the future; one on the importance of project management of research projects and one on the nature of research contracts between government and industry.

Firstly, the results of this project clearly indicate that the technical ability of the scientists and engineers engaged in research is not the only factor which can influence the success of a project. Good project management is an essential component of any successful project and should be regarded with weight equal to that of the technical aspects of the project. The more technically demanding the project and the greater the risk of the project not proceeding according to plan, the greater the need for good project management.

It is also essential the project management tools be understood by everyone involved and that the mechanisms to monitor and control the project be in place from the very beginning. It is also important to recognize the problems which can arise if the success of the project is largely dependent on the talents and abilities of one individual within a team. Thus, in future, the evaluation of any research proposal should include not only the technical ability and experience of the research team but the overall strength of the team and the ability and record of the research team as project managers.

Secondly, the intrinsically uncertain character of research must be taken into account in the terms and conditions which prescribe the responsibilities of the parties bound by the contract. Research is by its very nature, a tentative, indeterminate venture and any project which does not embrace a degree of technical uncertainty cannot be considered a research project. For this reason, research cannot be performed in the same way as a construction project and should not be measured by the same criteria. But while a research project cannot be expected to take the shortest route between two points, neither can it be allowed to wander without constraint. However, it is possible to control the progress of a project without stipulating what the final outcome will be.

The characteristic which distinguishes a rigidly planned construction project from a flexible, tentative research project is the existence of major decision points within the project which can significantly change the course of future work. One of the most crucial aspects of a project is the way in which the important decisions about whether to proceed, or in which direction to proceed with the research are made. Since research lies on the point of failure, lack of technical success on a project can become a deeply personal issue for those involved and they can often come to regard it as a mark of personal failure. It is important to

recognize that the lack of technical success or the inability to achieve the original objective of a project is neither a measure of the success of the project nor of the ability and integrity of the scientists and engineers engaged in the work. It is essential that the criteria for making important decisions are objective, that they are established well before the time for making the decision and that they are well understood by the entire project team from the beginning.

In future, government research contracts with industry should not stipulate the nature and attributes of the final product of the research but should describe how the research should be conducted. The terms of the contract should provide the guidelines which indicate which of the many possible directions are acceptable and which are not, and should stipulate the criteria by which the many decisions which will arise throughout the project will be made.

Essentially, the results of the project "Simulation of Bulk Mining at Depth with Backfill in Ontario Mines", reveals that a resolution of the technical uncertainties cannot always be assured and that the only reliable measure of a successful project is how well the project was structured and how well the work was managed.